CESARE'22
Coordinating Engineering for Sustainability and Resilience
May 6th – May 9th, 2022, Amman, Jordan

NZEB AND PASSIVE BUILDINGS: DILEMMAS AND CHALLENGES UNDER THE PRISM OF SUSTAINABILITY

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Keywords: nZEB, Passive House Standard, building energy performance, environmental performance, LCA.

Abstract. *As the buildings' sector is regarded responsible for a significant share of emissions, consumed energy and resources, the optimization of its energy performance was set as a priority for tackling climate change in many countries worldwide. Within this context, the EU introduced the concept of the nearly zero energy building (nZEB), and at the same time, other frameworks that promote building energy efficiency, such as the Passive House, gained wide acceptance and recognition. However, nowadays sustainability is pursued considering not only the use phase, but also every stage of the building's lifespan. The proposed study attempts to evaluate the concepts of nZEB and Passive House within the prism of energy and environmental performance through their application in a single family, prefabricated building, under the climate conditions of a warm and a cold region of Greece. In this way, the study highlights the differences between the two frameworks and draws attention to the design concepts that would constitute our buildings more energy-efficient and less carbon-intensive over their whole life cycle.*

1 INTRODUCTION

It is globally acknowledged that the climate crisis constitutes a serious threat to our lives and planet and that without a radical reduction of greenhouse gas emissions, global warming will exceed the limits set in the Paris agreement by the end of the century. Buildings are responsible for a significant share of consumed energy, emissions and used resources. In fact, it is estimated that almost 1/3 of CO_2 emissions and 40% of energy consumption are produced during the building use phase [1]. For this reason, the optimization of the building energy performance was set as a priority for tackling climate change in many countries worldwide decades ago. Pursuing such a goal shaped concepts, frameworks and requirements for assessing and evaluating the building energy performance.

Within this context, the EU introduced the concept of the nearly zero energy building (nZEB) in its directives and the state members developed regulations, tools and methods for calculating and assessing the building energy performance, taking into account the economic feasibility of the measures that would lead to the minimization of the consumed energy. In the Energy Performance of Buildings Directive 2010/31/EU, the nearly Zero-Energy Buildings (nZEB) were defined as "buildings with a very high energy performance, in which the very low amount of energy required should be covered to a significant extent by energy from renewable sources, produced on-site or nearby" [1].

At the same time, other concepts and schemes developed by individual institutions, such as the Passive House, gained wide acceptance and recognition by promoting even more energy efficient buildings, a goal that is achieved through the application of strict requirements for the building envelope and the building systems. The methodological approach of this specific standard is based on controlling energy flows with high levels of insulation, superior windows, low thermal bridging effect, high airtightness, ventilation with heat recovery, etc.

Nowadays, the concern of the EU is shifted towards the actual environmental performance of buildings. This is due to the acknowledgement that beyond the consumed energy and emissions, the building sector is responsible for the 50% of all extracted materials and 30% of the water consumption [2].

The question that logically arises is whether the imposition of stricter requirements as regards the building energy performance, which entails advanced thermal insulation, results in a sustainable building, considering the impacts on the environment throughout its whole life cycle. This stems from the fact that the environmental footprint of the building does not concern only the use phase but includes the embodied energy/carbon from the materials' production phase, as well as the energy/emissions from the deconstruction and waste phases, which are also dependent on the materials' quantities and characteristics.

Several studies have been focused on the life cycle analysis of energy efficient buildings. It has been found that the embodied energy of an energy efficient house throughout its life cycle is higher than the one of conventional buildings and can constitute almost half of life cycle energy [3]. In other published studies [4], low energy buildings appear to have a share of embodied energy between 23% and 58%; in passive buildings the share of embodied energy ranges between 11% and 57%, while the relevant share in the life cycle of conventional buildings ranges between 6% and 20%. Additionally, it is stated that the operating energy of low energy buildings appears to be higher than the one of passive buildings, but it has a lower relative contribution in their total life cycle energy [4]. The reduction of operational energy, which is the main objective of energy-efficient buildings, is mostly achieved by using more materials (e.g. insulation), which ultimately increase the embodied energy share in the total life cycle.

The proposed study will attempt to extract similar results through the comparative assessment of the application of the nZEB and the Passive House concepts in a small single family building. Although its objectives may seem similar to the studies mentioned above, the present work concerns a particular building system that has not been adequately studied before. It concerns a prefabricated building, i.e. a building consisting of factory-made components that are transported and assembled on site to form the complete structure.

1.1 A short overview of prefabricated buildings

In the past 50 years, emphasis has been given on the added value of industrialized architecture and technologies, which includes the ability to provide higher quality within minimum construction time and costs, increased possibilities for customization and adaptability, reduced environmental impacts and advanced sustainability [5]. Despite of the apparent advantages, the prefabricated residential buildings account for only 15% in Europe. Even lower penetration of prefabricated buildings designated for housing purposes is met in the Mediterranean countries [6]; for example, in Greece the rate of prefabricated residential buildings ranges around 2%. The main types of prefabricated building concern structures made of wood, reinforced concrete or steel, as well as composite systems, which usually combine concrete with steel elements. In low rise buildings (i.e. up to 2-3 storeys above ground) one of the most widespread prefabrication type employs the steel framework, due to the easiness and speediness of site installation, as well as the adaptability of the design to many architectural morphologies.

However, in most prefabricated steel constructions, the wall elements are made of lightweight panels, which do not participate in the structural performance of the building. This leads to the increase of the total steel weight, and consequently the cost and the environmental impact of the building. Besides, the use of light weight building elements decreases the thermal mass of such building types, with negative impacts on the control of interior temperature and increased possibility of overheating, thermal discomfort and increase of cooling energy needs during the warm period.

A practical and technical means to increase the thermal mass of lightweight buildings is to add elements made of heavy materials on the building enclosure, such as walls made by precast reinforced concrete, which has adequate thermal capacity. Concerning the precast concrete walls, two main types are discerned: monolithic elements and sandwich panels, both employing concrete for their construction. The monolithic concrete elements are made in the factory and they are joined together in situ either through especially designed connectors [7-9] or with cast-in-place concrete [10-12]. A drawback of this system is that it results to heavy and thick elements, which burden their handling and slow the installation process. The sandwich panels comprise of two (or three) concrete wythes that embed a layer of thermal insulation. In currently available solutions, the concrete wythes are made of concrete reinforced with steel bars in a mesh, carbon or glass textiles or fibres made of steel, glass or polypropylene [13]. The connection between the concrete wythes is realized with concrete connectors, metallic connectors or fibre reinforced polymer connectors [13] crossing through the insulation layer. The thermal insulation material is usually in the form of plates.

Within this framework, the research project SU.PR.I.M. (SUstainable PReconstructed Innovative Module) aims at the development of an innovative building module with advanced properties that will act as a vertical wall element in prefabricated residential buildings. This new building module will satisfy high requirements for its operation and performance. Specifically, it will be able to bear and deliver safely all the imposed building loads;

display advanced energy performance; demonstrate excellent hygrothermal behavior; provide acoustic insulation protection and resistance against fire actions; minimize its environmental footprint during its life cycle [14].

The multifunctional, innovative building element was developed through different studies, starting with the structural one and was optimized through the hygrothermal, energy, acoustic and fire performance studies [15]. Its main form is now finalized; it concerns a composite panel, composed of two lightly reinforced concrete plates, 5cm thick each, which are positioned on either side of vertical (and occasionally diagonal) metal hollow elements. The cavity between the metal hollow elements is filled with thermal insulation boards, and the whole wall element is insulated with ETICS. The type and the thickness of the thermal insulation materials may vary, in order to satisfy different needs, i.e. with regard to the climate, the requirements for acoustic insulation or fire performance, etc. The versatility of the new building element and its ability to adapt to different contexts and requirements, are listed among its significant advantages. The preconstructed composite system is described in the Greek Patent Application No. 20210100921, filed on 30-12-2021.

2 THE METHODOLOGICAL APPROACH

The objective of this paper is to examine the performance of a residential building through its whole lifespan, when studied for complying with the nZEB and the Passive House Standard requirements.

2.1 The examined building

The study concerns a small one-family building, presented in Figure 1. It has one storey and covers an area of 47.32 m². The plan is rectangular, expanded along the south-north axis, with openings only on the south (main façade) and north walls [16].

The walls of the building are constructed with the new SU.PR.I.M. building element. The floor and the roof are made of reinforced concrete. Above the upper slab, an inclined roof is positioned, constructed with structural steel elements and covered with clay tiles. The thermal insulation (XPS) is positioned on the external side of the building elements. Its thickness, as well as the window characteristics, are determined in order to comply with the regulatory frameworks applied in the study.

The energy performance of the building was assessed considering different climate conditions. It was assumed that the building was located in two different locations:

- One representative of the warmest climate zone of Greece (CMZ A: Heraklion, Lat. 35º19'N; Long. 25º08'E). Heraklion has a hot-summer-Mediterranean climate (Csa in the Köppen classification); summers are warm/hot and dry with clear skies and winters are mild with moderate rain.
- One for a colder climate zone (CMZ C: Thessaloniki, Lat. 40.30°N; Long. 22.58°E). Thessaloniki has a mild temperate climate (Cfa in the Köppen climate classification). Winters are rather dry and cool with common morning frost, whereas summers are warm and humid.

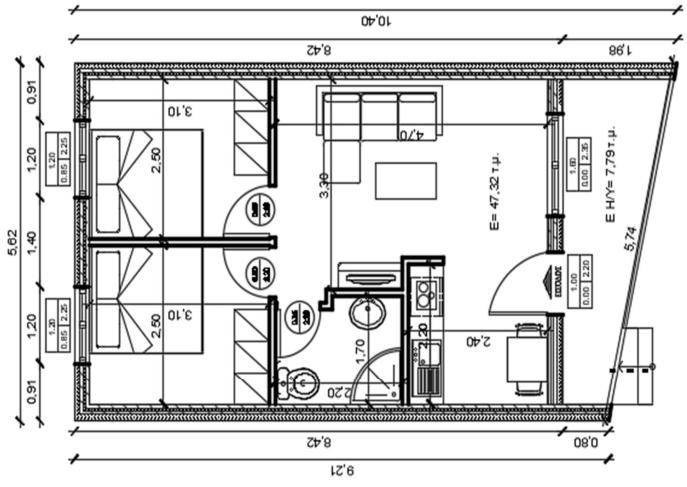


Figure 1: The plan view of the examined building.

Similar to the building configuration, the usage profile, the occupancy, the internal thermal loads, the ventilation patterns, etc., are selected along with the requirements set by each scheme, as presented in the following subsections.

2.2 The examined energy performance assessment schemes

The building configuration was selected in order to comply with the requirements of the two examined schemes, nZEB and Passive House, for each examined climate zone.

2.2.1 The nZEB approach

nZEBs are defined by each member state through its national regulation for building energy performance. In Greece, a building with nearly zero energy consumption has to belong to the energy category B+, which means that its primary energy consumption ranges between 50% and 75% of the respective amount of primary energy calculated for the reference building. Besides, the U-values of the building elements should be lower than a maximum value, which differentiate with regard to the climate zone (Table 1).

Building element	Heraklio -Zone A		Thessaloniki-Zone C	
	Maximum thermal transmittance Umax [W/(m² K)]	Minimum thermal insulation thickness d [m]	Maximum thermal transmittance Umax [W/(m² K)]	Minimum thermal insulation thickness d [m]
Wall	0.55	0.05	0.40	0.08
Window	2.80	-	2.40	-
Roof	0.45	0.06	0.35	0.10
Floor above ground	1.10	0.01	0.60	0.04

Table 1: The requirements for the thermal performance of the building elements set for nZEBs in the examined climate zones for the specific building.

For all zones, the windows comprise of an aluminium frame with thermal break and a double, low-e glazing, with an average value of 2 W/(m² K). The heat transfer coefficient from thermal bridges ($\Sigma(\Psi x \ell)$) was calculated and found equal to 22.83 W/K. The majority of thermal bridges are observed along the conjunction of the floor and the roof with the walls. The thermal bridges account for approximately 25% of the heat transfer coefficient of the whole building envelope.

According to the Building Energy Performance Regulation, the residential buildings operate 18 hours per day all year long. The thermostat is set to 20ºC in winter and 26ºC in summer. The ventilation rate is set to 15m^3/h/person, and it is assumed that there are 5 persons per 100m^2 of space. The infiltration rate was found equal to 13.05 m^3/h.

The above data, along with information regarding the optical properties of the windows and the opaque elements, the shading factors, the thermal mass, the characteristics of the building systems, are used by the national building energy performance calculation tool (TEE KENAK) in order to estimate the energy needs, the final energy and the primary energy consumption. The calculation tool employs the quasi-steady calculation described in the ISO 13790.

2.2.2 The application of the Passive House Standard

The criteria that a building should fulfil in order to be characterized as a Passive House are [17]:

- The energy demand for heating should not exceed 15 kWh/m^2 or the peak demand should not exceed 10 W/m^2.
- The energy demand for cooling should not exceed 15 kWh/m^2, with an additional allowance for dehumidification, or the peak demand should not exceed 10 W/m^2.
- The Renewable Primary Energy Demand, the total energy to be used for all domestic applications (heating, hot water and domestic electricity) should not exceed 60 kWh/m^2 per year (for Classic).
- The infiltration is set at a maximum of 0.6 air changes per hour at 50 Pascals pressure (ACH50.
- Thermal comfort must be met for all living areas during winter as well as in summer, with not more than 10 % of the hours in a given year over 25°C.

Climate zone	Thermal transmittance window [W/(m^2 K)]	Thermal transmittance wall/roof [W/(m^2 K)]	Hear recovery efficiency [%]	Glazing type
Warm Heraklion -Zone A	1.25	0.5	Energy Recovery for humid summer	Double low-e glazing
Warm-temperate Thessaloniki-Zone C	1.05	0.3	75	Triple low-e glazing

Table 2: Recommended characteristics for the building envelope and systems by the Passive House Standard [17].

There are no specific requirements for the thermal transmittance of the building envelope, but only recommendations with respect to the climate zone. The U-values and the properties of the components that are recommended for the examined sites, are presented in Table 2. According to the Passive House Institute's climate classification, Heraklion belongs to the warm zone and Thessaloniki to the warm-temperate one.

In order to comply with the requirements of the Passive House criteria, it was found through the analysis that the examined building should have the characteristics presented in Table 3. Accordingly, the windows consist of aluminium frames with thermal break (U_f = 1.00 W/(m^2 K)) and double low-e glazing with argon (U_g = 1.00 W/(m^2 K)), when the building is located in the warmer climate (Zone A), and triple low-e glazing with argon (U_g = 0.60 W/(m^2 K)) when the building is located in the colder climate (Zone C).

Airtightness is merely guaranteed through the internal plastering of all wall and roof elements, as well as by the use of special membranes on the joints of elements, around penetration for wires and ductwork. Through the careful design and construction, the infiltration is expected to be limited to 0.6 air changes per hour at 50 Pascals pressure, which is one of the Passive House Standard criteria.

Mechanical ventilation is provided with one heat exchanger unit with 88% thermal efficiency and air flow that ranges from 54 to 222 m^3/h. Heating and cooling are provided through an air-to-air heat pump, with a capacity of 9000 BTU and an efficiency ratio equal to 3 for heating and 6 for cooling.

The estimation of the energy parameters is made with the Passive House Planning Package (PHPP), which is organized in the form of a spreadsheet workbook and includes tools for energy balances, windows configuration, heating load calculation, summer comfort assessment, etc.

Climate zone	Thermal insulation thickness: wall [m]	Thermal insulation thickness: roof [m]	Thermal insulation thickness: floor [m]
Warm Heraklion -Zone A	0.05	0.15	0.05
Warm-temperate Thessaloniki-Zone C	0.15	0.20	0.10

Table 3: Selected thermal insulation thicknesses for complying with the Passive House requirements.

2.3 The assessment of environmental impact

Main goal of the study was to evaluate impacts and contribution of a) materials through the building's life cycle and b) the building's operation. The environmental impact is assessed through the life cycle assessment, which follows the principles of ISO 14040, ISO 14044, EN 15804 and EN 15978 for all processes within the system boundaries, extending from the materials' production to the disassembly and disposal stage. The included processes are:

- The upstream processes (A1-A2-A3, i.e. raw material, supply, transport, manufacturing).
- The core processes (A4-A5, i.e. transportation, building construction).
- The downstream processes (B4-B6-C1-C2-C3-C4, i.e. building operation, maintenance, demolition, transportation to the management facility).

The LCI data are provided by the Ecoinvent database and they, combined with other input data (quantities and properties of material/components, transportation distances) derived from the building construction plans, the Greek market and constructional techniques, provide the necessary information for all the upstream (A1, A2, A3) and core (A4, A5) processes of the analysed buildings.

The consideration of each material's and component's reference service life (derived from international

literature, ISO 15686-8 and EN 15459) lead to the calculation of the impact that relates to their replacement (B4) during the building's life cycle. The operating (B6) environmental impact calculations are based on the results of the energy performance analysis (inputs) and the consideration of an air-to-air heat pump for heating and cooling. The end-of-life scenario relates to the demolition/deconstruction (C1) of the building at the end of its life cycle and the transportation (C2) of the waste to the nearest management facility (50 km distance). The present analysis does not consider any procedures for the waste management due to the lack of available or reliable data for Greece [16].

Finally, the environmental impact is calculated per square meter of reference/heated building area, for the 50-year building lifespan and for the impact indicators of methods CML-IA Baseline and Cumulative Energy Demand (CED. The main assessment indicators are the embodied energy and CO_2 emissions, represented by the CED and global warming impact categories.

3 THE BUILDING ENERGY PERFORMANCE

For both design standards the primary energy consumption of the building for covering the heating, cooling and hot water preparation was calculated, using the relevant calculation tools, for the two examined locations.

The amount of primary energy consumed per year when the nZEB requirements are met is presented in Figure 2.a. There is a remarkable differentiation on the total primary energy calculated for the two locations; the amount needed for covering the requirements in the warmer zone is 60% lower than the one needed for the colder zone. This difference is obviously associated with the heating demand, which is higher in the colder regions of the country. The cooling requirements are slightly higher for the warm zone and by no means can they counterbalance the substantial differentiation on the heating ones.

When applying the Passive House Standard, the picture is different (Figure 2.b.). The annual primary energy consumption for heating, cooling and hot water preparation is lower than the previous case; actually the amount is higher for the warm zone than for the colder one. In fact, the heating demand is slightly higher for the colder zone, but the cooling demand is almost doubled in the warm location. It must be noted that in general the PHPP incorporates the use of electricity for household appliances in the calculation of primary energy consumption, but this amount is not considered in these figures.

The differences between the energy performance of the building configured under the two design standards show the affect of the thermal protection level of the building elements, expressed through the thickness of the thermal insulation layer and the properties of the windows, as well as the minimization of infiltration and the use of ventilation with heat recovery. It is depicted that through the limitation of thermal losses from the building envelope and ventilation, the impact of climate conditions on heating needs can be minimized, but this is not the case when it comes to the cooling demands.

Over the whole building operation phase (assumed to be 50 years) the consumed energy for the nZEB standard is lower by 18% in the warm climate conditions and higher by almost 37% in the cold climate conditions, when compared with the respective amounts calculated for the application of the Passive House requirements. It must be noted, however, that the differences are influenced by the use of different calculation tools.

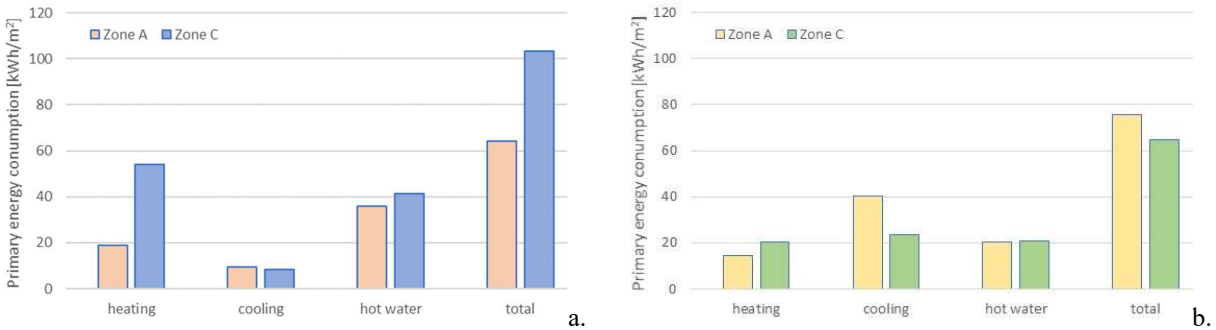


Figure 2. The primary energy consumption of the building calculated with respect to a) nZEB and b) Passive House requirements for both examined locations.

4 THE BUILDING ENVIRONMENTAL PERFORMANCE

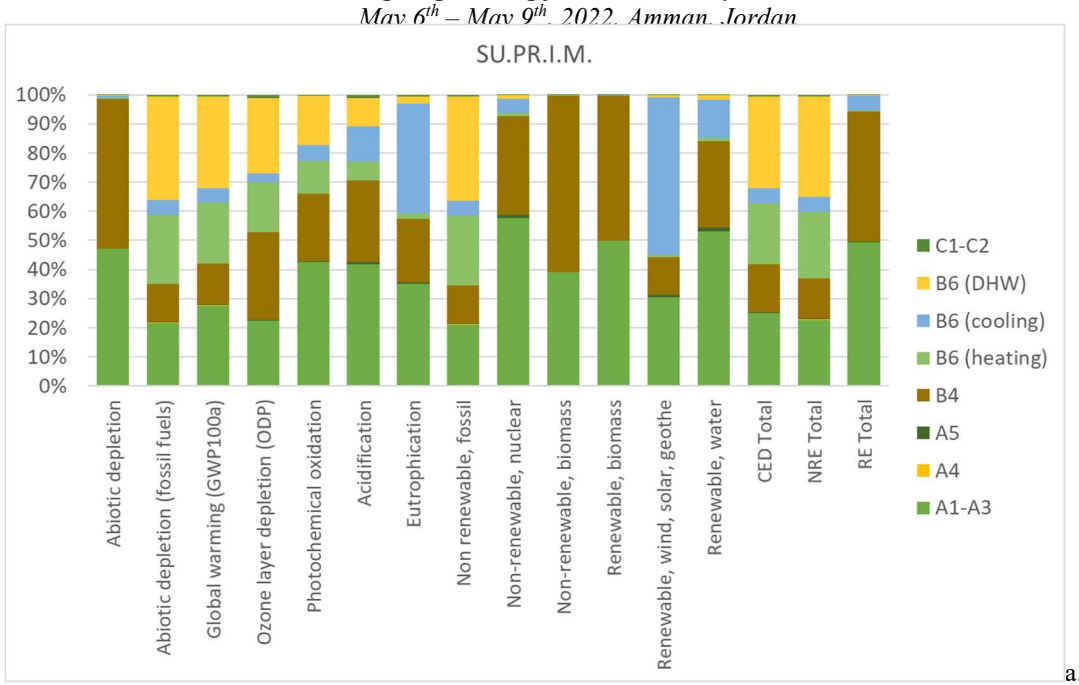
Before indicating the differences in the environmental performance derived from the two design schemes, it is worth studying the building in its normal configuration, provided that it is constructed with the use of the new, composite prefabricated wall element. The majority of the prefabricated buildings constructed by the company are located in Northern Greece and they are insulated with a 10 cm thick layer of XPS positioned on the external side of the building envelope. Figure 3 shows the building's performance for each life cycle process, as well as the contribution of each material and process to the configuration of the embodied environmental impact.

The contribution of each life cycle process to the total life cycle impact of the analysed buildings varies between the impact categories (Figure 3). For the scenario of the nZEB building located in Zone C (wall insulation thickness 10cm, climate zone C), the average impact contribution (including all indicators) for the upstream processes (A1-A3) is calculated at 36.6%, while the core processes (A4-A5) contribute with an average of 0.5% to its total life cycle impact. The replacement process (B4) of materials/components correlates with an important average share of 28.5%, while the operating phase (B6) with a total of 33.9% (heating 9.5%, cooling 10.1%, DHW 14.3%). Finally, the downstream processes (end-of-life, C1 and C2) relate only to 0.5% share of the life cycle impact, which correlates with the exclusion of the waste management processes (C3, C4) from the system boundaries due to the lack of available/reliable data for the Greek region. Considering only the embodied impact (Figure 3.b), the results highlight the increased average contribution for the windows (12.04%), the heating/cooling system, the XPS insulation and the steel sections. However, the break-down analysis for the embodied impact contribution depends strongly on the impact indicator and on the composition of each respective material/component. For instance, concrete relates to 13.72% contribution in the GWP indicator, while its lower embodied impact in the remaining indicators leads to an average contribution of 4.95%.

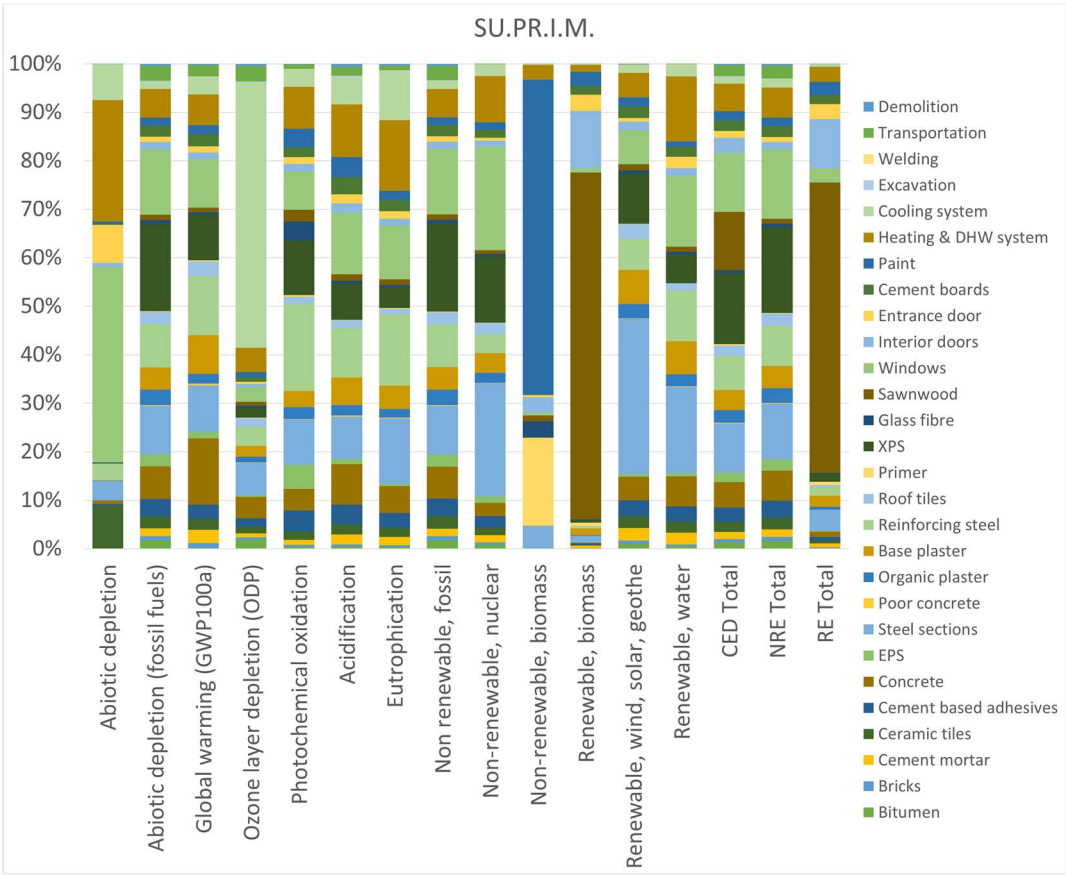
Conforming with the requirements of the Passive House Standard affects the environmental impact of the building, mainly due to the necessity of installing additional insulation materials, superior windows and the ventilation system on one hand and the reduced energy consumption during the operation phase on the other. As expected, the impact is more significant for the upstream (A1-A3) and the maintenance (B4) processes; indicatively, Figure 4 shows the increase of the impact indices assessed for the building designed according to the Passive House Standard for the two climate zones considering the increase of thermal insulation. The indices of global warming and CED are increased by 5% and 8% for the warm climate and by 8% and 14% respectively for the colder zone. Beyond these two very important indices, which are associated with climate change, abiotic depletion and photochemical oxidation are also affected. Similar are the results for the windows; the necessity of using a window with a triple glazing in the cold zone for the Passive House design scheme lead to the increase of the environmental impacts, especially as regards the photochemical oxidation (by 44%), the eutrophication (by 23%), the abiotic depletion (by 11%), the global warming potential (by 11%) and the CED (by 9%) compared to the relevant impacts caused by the use of the double glazing.

The use of energy during the building operation, calculated for the 50 year lifespan, differentiates among the two design schemes, as presented in the previous section. This differentiation leads to analogous differences in the CO_2 emissions; with the implementation of the Passive House Standard, the CO_2 emissions are increased by 17% in the warm zone and decreased by 34% in the cold zone.

It is obvious from the analysis that the increased requirements of the Passive House institute lead to additional environmental impact when the building is located in a warm zone, where the superior thermal shielding does not offer substantially to the building energy performance. On the other hand, in colder climates the reduction of energy consumption is very remarkable and the environmental benefits stemming from it can counterbalance, at some extent, the burdens from the super insulated building envelope. Similar outcomes have been reached in other studies, which conclude that the application of the PH standard does not always result in a competitive advantage in terms of improvement of the holistic building sustainability in a warm climate [18]. And even in cases where the operational energy was minimized, the dramatic contribution of materials-related impacts emerged [19].



a.



b.

Figure 3.a. Life cycle impact of the building per impact category and life cycle process within the system boundaries. b. Percentage contribution of each material/component/process to the embodied impact of the building per impact category (scenario XPS 10cm scenario and climate zone C of Greece).

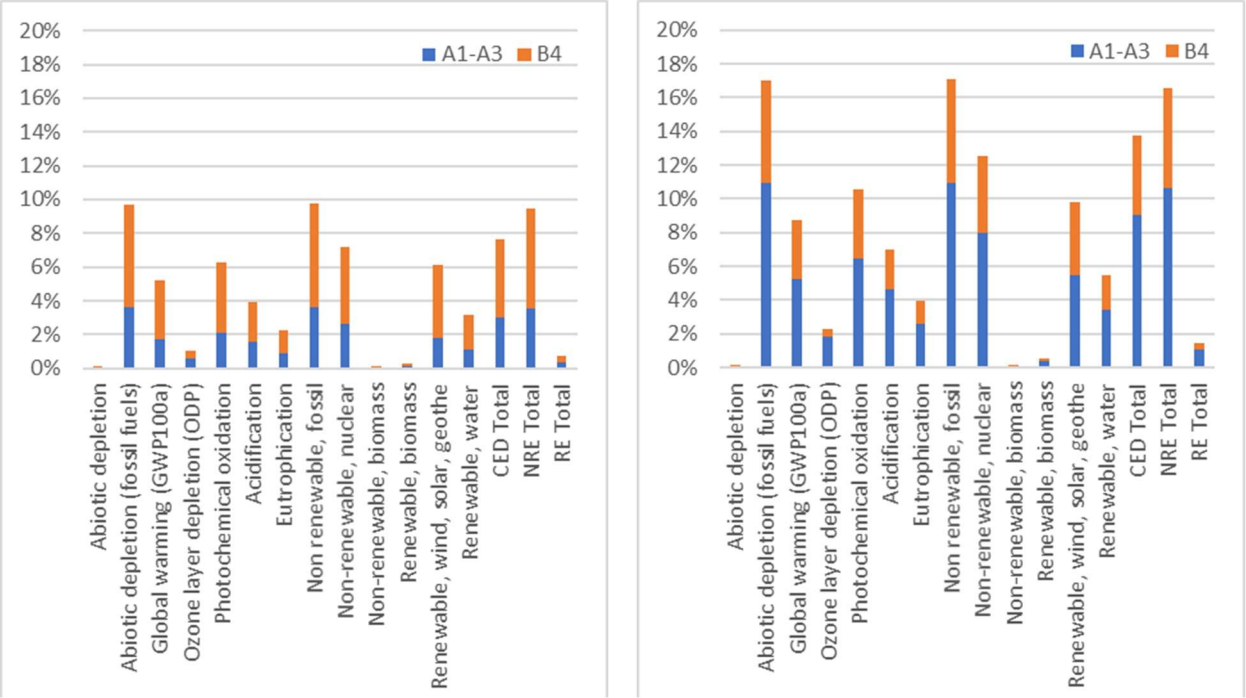


Figure 4. Differences on the environmental impacts of the building in A1-A3 and B4 processes due to the increase of the thermal insulation for conforming with the Passive House Standard when the building is located in the warm and the cold climate of Greece.

5 CONCLUSIONS AND DISCUSSION

The application of two energy performance schemes on a building located in different environments provided interesting results. Both examined schemes target to energy efficient buildings, but they are based on different concepts: the nZEB scheme sets requirements for the building envelope and systems and require the utilization of renewable energy sources; the Passive House scheme imposes very strict requirements on the thermal insulation level, the thermal bridging effect and the windows as well as the incorporation of a mechanical ventilation system.

The analysis showed that when the building is located in the warm region, its energy and environmental performance is better when the nZEB scheme is applied. It seems that the superior thermal insulation of the building envelope imposed by the Passive House Standard does not allow for the dissipation of heat towards the ambient environment and creates additional needs for cooling and dehumidification. The environmental footprint then becomes bigger and is further intensified by the need for additional materials.

In the case of the colder climate, the energy performance is substantially improved with the application of the Passive House requirements, considering that the reduction in energy consumption reaches 34%. However, when it comes to the environmental impact, the results are not equally astonishing; the initial goal of sustainability seems to be reached, but to a much lower extent, given that the higher embodied burdens were compensated by the remarkable operational energy savings.

Besides the energy and environmental performance, another very important issue that is directly related to the application of the energy performance schemes, is the extra costs. The financial burden from installing the extra thick layers of thermal insulation, the superior windows and the ventilation system with its relevant ductwork imposed by the Passive House is substantial. The cost increases by the necessity of employing a Passive House designer to study the building, provide guidance advice during the construction in order to guarantee airtightness and minimum thermal bridges and take the necessary actions in order to certify the building after its construction.

From all the above it is concluded that it is not only the reduction of operational energy that could lead to a sustainable building. Especially for buildings with advanced energy performance, the role of materials gains much significance. It is in the hands of the engineers to make good choices based on the optimal energy and environmental performance throughout the building life span considering both costs and the constructional implications.

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ACKNOWLEDGEMENTS

Part of this research has been co-financed by the European Regional Development Fund of the European Union and Greek national funds through the Operational Program Competitiveness, Entrepreneurship and Innovation, under the call RESEARCH – CREATE – INNOVATE (project code:T1EDK-03042) and under the action "Innovation Coupons for the SMEs of the Prefecture of Central Macedonia".